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Fingerprints of the Hierarchical Building up of the Structure on the Mass-Metallicity Relation

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ABSTRACT

We study the mass-metallicity relation of galactic systems with stellar masses larger than 10^9 $\mathrm{M}_{\odot}h^{-1}$ in ΛCDM scenarios by using chemical hydrodynamical simulations. We find that this relation arises naturally as a consequence of the formation of the structure in a hierarchical scenario. The hierarchical building up of the structure determines a characteristic stellar mass at $M_c \approx 10^{10.2}$ $\mathrm{M}_{\odot}h^{-1}$ which exhibits approximately solar metallicities from $z \approx 3$ to $z = 0$. This characteristic mass separates galactic systems in two groups with massive ones forming most of their stars and metals at high redshift. We find evolution in the zero point and slope of the mass-metallicity relation driven mainly by the low mass systems which exhibit the larger variations in the chemical properties. Although stellar mass and circular velocity are directly related, the correlation between circular velocity and metallicity shows a larger evolution with redshift making this relation more appropriate to confront models and observations. The dispersion found in both relations is a function of the stellar mass and reflects the different dynamical history of evolution of the systems.

Key words: galaxies: formation - evolution - abundances - cosmology: theory - methods: numerical

1 INTRODUCTION

Our knowledge of the chemical evolution of the Universe has improved dramatically in the last years as the result of the high precision data gathered on local and high redshift galaxies and on the interstellar and intergalactic media. In particular, estimates of the evolution of the well-known local luminosity-metallicity relation suggest a change in the zero point and slope so that at a given metallicity, systems are brighter in the past (Kobulnicky & Kewley 2004; Maier et al. 2004; Shapley et al. 2004). Lequeux et al. (1979) first claimed that the fundamental relation was actually between stellar mass and metallicity. Recently, Tremonti et al. (2004) confirmed the existence of the stellar mass-metallicity relation (MMR) on statistical basis for a sample of galaxies in the Sloan Digital Sky Survey (SDSS). These authors detected a change in the slope of this relation at a stellar mass similar to the characteristic mass defined by Kauffmann et al (2003). Tremonti et al. (2004) suggested that the steeper slope found in this relation for smaller stellar masses was the result of the action of galactic winds. Recently, Gallazzi et al. (2005) found that stellar mass is not the fundamental parameter determining age or metallicity based on the large dispersions found in their data. The physical origin of both the luminosity-metallicity and the mass-metallicity relations, their interconnection and evolution are fundamental problems for models of galaxy formation.

High precision, large-scale cosmological observations provide strong support for ΛCDM models. In this scenario, galaxies form by the hierarchical aggregation of substructure. Hence, mergers and interactions as well as continuous gas inflows play a crucial role in the history of evolution of galaxies, affecting the mass distributions and star formation rates, and as a consequence, the chemical properties of the systems. In order to study galaxy formation and to provide a consistent concatenation and interpretation of observational results, sophisticated models which can follow the hierarchical building up of the structure together with the evolution of their chemical properties are needed. Cosmological hydrodynamical models which include chemical production are a powerful tool to tackle this problem as it has been previously shown by Mosconi et al. (2001) and Lia et al. (2001), among others.

The main goal of this work is to discuss the direct relation between the dynamical evolution and chemical properties of galactic systems in a hierarchical clustering scenario,

in order to provide clues on the origin of the fundamental metallicity relations of galaxies. Note that this paper is focused on the study of systems with stellar masses larger than $10^9 M_\odot h^{-1}$. Hence,results may not be relevant for dwarf galaxies, where SN are expected to play a more important role Although we do not include a strong Supernova (SN) energy feedback in this paper, we discuss its potential action on the results.

This Letter is organized as follows. Section 2 describes the numerical simulations, the methodology applied to estimate the chemical and astrophysical properties of galactic systems and the findings. Section 4 summarizes the main conclusions.

2 ANALYSIS AND RESULTS

We have run cosmological hydrodynamical simulations which describe the evolution of dark matter and baryons in a ΛCDM scenario ($\Omega = 0.3, \Lambda = 0.7, \Omega_b = 0.04$ and $H_0 = 100\ h\ \mathrm{km\,s^{-1}Mpc^{-1}}$, $h = 0.7$) including metal-dependent radiative cooling, star formation and chemical enrichment by Supernovae II and Ia. The chemical algorithms have been developed within the code GADGET-2 in its fully conservative version (Scannapieco et al. 2005). The simulation corresponds to a 10 Mpc h^{-1} side cubic volume resolved with initially 2×160^3 particles, implying a mass resolution of $1.7 \times 10^7\ M_\odot\ h^{-1}$ and $2.0 \times 10^6\ M_\odot$ for the dark matter and gas, respectively. We have assumed an instantaneous thermalization of the supernova (SN) energy.

Virialized structures are identified at different redshifts by using a combination of a friends-of-friends technique and a contrast density criterium ($\delta\rho/\rho \approx 178\Omega^{-0.6}$). The dynamical and mean chemical properties of these systems, as well as their star formation histories, are estimated taking into account the mass within the optical radius, defined as the one that encloses 83% of the baryonic mass. Since these simulations follow the chemical enrichment by individual elements, we can directly estimate abundance indicators such as $12 + \log(\mathrm{O/H})$. We have chosen to work with mass-weighted abundances since they reflect more reliably the chemical enrichment of the system as a whole. Caution should be taken when comparing these abundances with observations that provide information only on certain regions of galaxies such as HII regions.

We have constructed the stellar mass-metallicity relation and the circular velocity-metallicity relation for galactic systems at different redshifts. The circular velocities (V_{opt}) are measured at the optical radius. For the gas component, we find that the scatter in the relations is much larger and their evolution is not that clearly defined, although the gas follows the same general trends defined by stars (see De Rossi et al. 2005, in preparation). For that reason, in this Letter we estimate the metallicities from the simulated stellar populations.

In Fig. 1 we show the MMR estimated for the galactic systems at $z = 0$, renormalized by 0.25 dex to match the zero point of the observed relation given by Tremonti et al. (2004; shaded areas). We note that this displacement is not needed for the gas component which is always more enriched than the overall stellar population. However, we would also like to point out that the metallicities corresponding to the

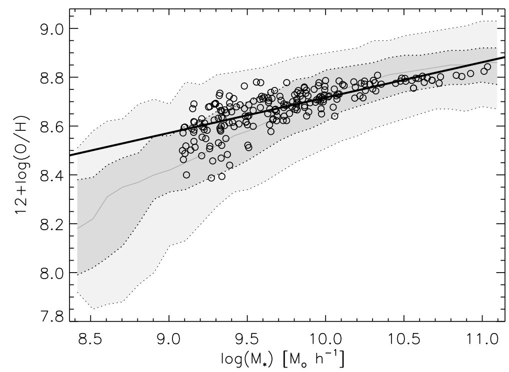

Figure 1. Mass-metallicity relation for the simulated galactic systems at $z = 0$ in a Λ-CDM scenario (open circles). The shaded areas correspond to one and two σ regions from the observed relation of Tremonti et al. (2005). We have also included a linear regression fit to the simulated points for comparison (solid line).

SDSS have been obtained from the central regions of galaxies which are expected to be more metal-rich. As it can be seen from this figure, a linear regression fit is not a good representation of the simulated relation. However, the simulated MMR is in agreement with the trend estimated from the SDSS, although there is some excess of metals at the lower mass end.

In Fig. 2 we show the stellar mass-metallicity relation for galactic systems at different redshifts. We can appreciate that the MMRs behave in a similar fashion from $z = 3$ to the present time. As it can be seen from this figure, there is a change in the curvature at $M_c \approx 10^{10.2}\ M_\odot h^{-1}$ which corresponds to an abundance of $12 + \log(\mathrm{O/H})_c \approx 8.7$. This characteristic mass has been estimated by determining the stellar mass where the linear fit is no longer a good representation of the simulated data. This has been achieved by the analysis of the residuals of these relations. We estimated the stellar mass at which the residuals show a behaviour which departures from that expected for a good linear fit. As it can be seen in Fig. 3, for $M_* \geq M_c$, the residuals start to be systematically negative indicating a saturation of the metallicity as a function of stellar mass. For all analysed redshifts, the relations determined by the systems with stellar masses greater than M_c tend to have a shallower slope, although the level of enrichment increases with redshift. Conversely, systems with $M_* < M_c$ show a steeper correlation between metallicity and stellar mass. The error bars in Fig. 2 denote the statistical dispersion of the abundances in each bin. These dispersions show a larger scatter in oxygen abundances for $M_* < M_c$ which suggest that the histories of evolution of these systems are more different among each other than those of the systems at the massive end (a similar trend is found by binning in mass intervals with equal number of members).

The redshift evolution of the MMR relation indicates an

increase with time of the chemical content of the systems, with the major changes driven by the smaller ones which, on average, are enriched by up to ≈ 0.10 dex from $z \approx 3$ to $z = 0$. This behaviour is responsible of a general flattening of the slope in this mass range. Systems with $M_* > M_{\rm c}$ show less evolution in their chemical content with a $\approx$0.05 dex variation from $z = 3$ to $z = 0$. The characteristic mass remains almost unchanged with redshift (Fig. 3) while its corresponding oxygen abundance increases only by 0.05 dex in the same redshift range.

The different histories of evolution of the systems may be determining the dependence of the metallicity evolution and dispersions on stellar mass. In order to investigate this point, we estimated the time (τ_{50}) when 50% of the total stellar mass at $z = 0$ was already formed for each galactic system. This time τ_{50} is defined by the particular evolutionary history of each galactic system. As expected, we found that objects with $M_* > M_{\rm c}$ have older stellar populations with a variation of up to $\approx 15\%$ in τ_{50}. Conversely, the stellar populations of the smaller mass systems present a wider range of ages, leading to a change of more than 30% in τ_{50}. Hence, while most of the stellar content of massive systems is formed at higher redshift as expected in this kind of cosmological scenario, smaller systems constitute a diverse population.

In order to understand the physical meaning of the evolution of the MMR and the characteristic mass $M_{\rm c}$, we have analysed the merger trees of the simulated systems at $z = 0$ and the relation between the dynamical and chemical properties of their progenitors at $z > 0$ (De Rossi et al. 2005, in preparation). From the analysis of the merger histories we find that systems with $M_* < M_{\rm c}$ transform their gas content into stars in a more passive fashion or via gas-rich mergers, setting a steeper correlation between stellar mass and metallicity. Galaxies with masses larger than $M_{\rm c}$ are formed by merger events which involve stellar dominated systems. In these cases, the mergers produce a system with a final stellar mass equal to the sum of the old stars in the merging objects plus some new born ones, while its overall mean abundances remain at the same level of enrichment. This situation occurs because, in this case, the merging systems have already transformed most of their gas into stars so that there is no fuel for an important starburst during the merger. It could be also possible that a large system merges with a smaller less-enriched one which can feed new star formation activity but with lower level of enrichment. Both scenarios have the same flattening effect on the slope of the mass-metallicity relation in systems within this range of masses.

We also calculated the circular velocity -metallicity relation as shown in Fig. 4. We used the same mass intervals as in Fig. 2 in order to estimate the mean velocity of the corresponding galactic systems and their standard deviation in each mass interval. We can appreciate from this figure that, at a given redshift, the faster a system rotates, the higher its metallicity. At a given velocity, the chemical evolution with redshift is larger than that obtained at a given stellar mass. This is because as one moves to lower redshift, more massive systems start to contribute to the lower circular velocity intervals. At high redshift, galactic systems are more concentrated with less mass required to get to higher velocities. This reflects the fact that as the Universe expands and its mean density decreases, galactic systems do not need to reach so high densities to form bounded structures. Although the circular velocity determines a clear correlation, it shows larger evolution with time than the MMR. If the circular velocity of a system is known, the redshift of the systems is also needed to establish its metallicity, otherwise the dispersion could be as large as ≈ 0.35 dex.

In the simulations analysed in this Letter, we have not included a treatment of energy feedback, which is expected to produce powerful outflows, affecting the star formation process and the metal production and mixing. Hence, the treatment of energy feedback may introduce changes in the metallicity properties. Taking into account previous results, SN feedback is expected to affect more strongly systems with circular velocities smaller than 100 km s^{-1} (Larson 1974). In this case, only the smallest systems in Fig. 4 would be significantly affected. Note that the velocity corresponding to the characteristic mass varies from around 300 km s^{-1} at $z = 3$ to 140 km s^{-1} at $z = 0$ and consequently, it is unlikey that $M_{\rm c}$ will be significantly modified either. At $z = 0$, the strongest effects of energy feedback are expected to take place in the small mass range where we detect an excess of metals (see Fig 1). The action of strong SN feedback would produce the ejection of part of the enriched material out of the systems and the decrease of the general level of enrichment.

The need for SN outflows is also suggested by the analysis of the effective yields (defined as $y_Z = Z/\ln(\mu)^{-1}$ where Z is the gas-phase metallicity and μ the gas fraction of the systems). The simulated y_Z values are lower than the solar yield expected in a closed box model, since our systems formed in a hierarchical scenario where mergers, interactions and infall affect the mass distribution and regulate star formation. Contrary to observations (e.g. Garnett 2002), we found slightly larger $y_{\rm Z}$ for systems with $10^9 {\rm M}_{\odot} h^{-1} < M_* < M_{\rm c}$ compared to those of the massive ones ($M_* > M_{\rm c}$), which supports the claim for stronger SN outflows for the former. In the case of massive systems, we get a mean of y_Z which remains approximately constant with optical velocity. Although this latest result is in agreement with Garnett (2002), it might be indicating the need for some ejection of material also in massive systems in the light of the new observational findings of Tremonti et al. (2004).

3 DISCUSSION AND CONCLUSIONS

We have shown that galactic systems in the concordance ΛCDM model reproduce a stellar mass-metallicity relation in general agreement with that measured for galaxies in the SDSS at $z \approx 0$, as a result of the particular evolution of galactic systems in this kind of scenarios. We acknowledge an excess of metals at the low mass end which could be solved by strong SN energy feedback.

We found a stellar mass-metallicity relation well-defined from $z = 3$ which evolves weakly with time. The largest change in the metal content is driven by the smaller mass systems. We have also determined a characteristic stellar mass (corresponding to solar abundance) so that for more massive systems, the mass-metallicity relation flattens and there is less evolution in their chemical enrichment level. This characteristic mass and its corresponding metallicity are robust against numerical resolution since approximately

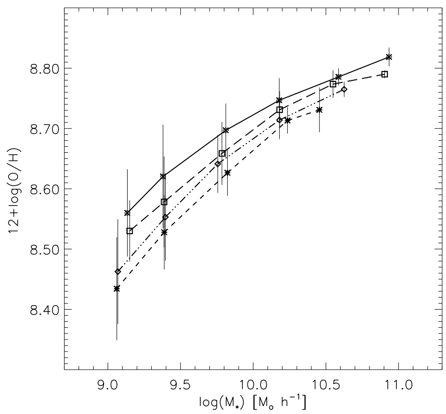

Figure 2. Mean mass-metallicity relation for galactic systems identified at $z = 3$ (short-dashed lines), $z = 2$ (dotted-dashed lines), $z = 1$ (long-dashed lines) and $z = 0$ (solid lines) in a Λ-CDM scenario . Error bars correspond to the standard rms dispersions.

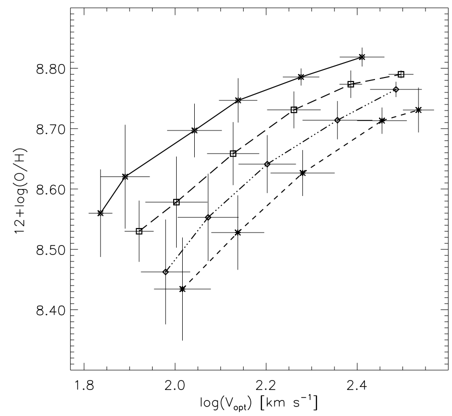

Figure 4. Mean circular velocity-metallicity relation for galactic systems at the same redshifts shown in Fig. 2. Error bars correspond to the standard rms dispersions.

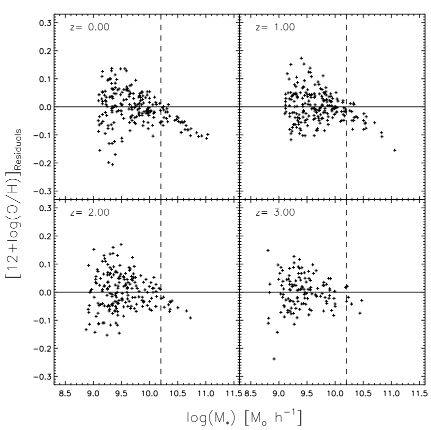

Figure 3. Residuals of 12+log (O/H) with respect to a linear regression fit to the relation between metallicity and stellar mass at redshifts of Fig. 2. The dashed lines show the stellar mass at which the residuals are systematically negative because of the change in the slope of the stellar mass-metallicity relation.

the same values are detected in experiments run with different number of particles, from 50^3 to 160^3.

The characteristic mass found from our simulations agrees with the one estimated from the SDSS by Kauffmann et al. (2003). This mass appears naturally as a result of the hierarchical building up of the structure and segregates two distinctive types of galactic systems. Our findings show that systems with $M_* > M_c$ transform most of their gas into stars at higher redshifts and experience important merger events. At lower redshifts, these mergers tend to involve systems dominated by stars so that while the final stellar mass of the outcoming system is larger, its mean stellar metallicity remains basically the same. This is because a small percentage of new stars are formed during the merger and, consequently, the final metallicity is determined by the old stars belonging to the incoming systems. Smaller galactic objects form their stars in a more passive way or during gas-rich mergers. Hence, in this case, there is a more steeper correlation between metallicity and stellar mass content.

According to our results, in the absence of strong SN energy feedback, the stellar mass-metallicity relation is the parameter that better determines the metallicity of a galaxy with a weak dependence on redshift. Conversely, at a given circular velocity, the combination of chemical enrichment and cosmology produces a larger evolution with lookback time. We found that the dispersions in both relations are produced by the combination of stars with different ages and metallicities which results from the particular dynamical history of evolution of a system in a hierarchical clustering scenario.

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